communications
earth & environment

COMMENT

https://doi.org/10.1038/s43247-023-01068-x OPEN

Why blue carbon cannot truly offset fossil fuel emissions

Sophia C. Johannessen [1✉] & James R. Christian[1]

Blue carbon will not solve climate change. The effect is too small; existing sediment carbon stock is a liability; and there is a timescale mismatch between ancient fossil fuel emissions and uptake by vegetation. Clearer communication would support informed decision-making.

Introduction: a communication gap

The global climate is changing dramatically as a result of excess carbon dioxide in the atmosphere. Nature-based solutions, such as the expansion or protection of forests or coastal blue carbon ecosystems—mangroves, salt marshes, seagrass meadows, seaweed—have been proposed as a means to offset emissions and reduce the effects of climate change. However, there is considerable public confusion about the mitigation potential of such nature-based solutions.

Media articles use extravagant language to describe the potential for blue carbon to mitigate climate change. Headlines include phrases like: "the secret weapon in the fight against climate change," "the carbon-fixing superpower of wetlands," and "the hidden CO_2 sink that… could save the planet" (Box 1a). These headlines reflect the enormous carbon sequestration rate claimed for blue carbon ecosystems in the scientific literature, e.g., that, while occupying only 0.5% of the seafloor, these ecosystems are responsible for more than half of the carbon burial in the ocean[1], or that seagrass meadows alone bury 10–18% of the organic carbon buried in the ocean, in <0.1% of the area[2].

The carbon sequestered by vegetated ecosystems is often presented as being equivalent to the carbon released by fossil fuel burning. This equivalency appears in media articles, blogs by non-governmental organizations, and even scientific papers (Box 1b). It is implicit in statements that protecting or expanding a particular blue carbon ecosystem will offset the emissions of a certain number of cars, coal-based power plants, etc. This is the basis for carbon offset and carbon credit schemes.

However, the protection or expansion of blue carbon ecosystems can only make a very limited contribution to solving the problem of excess atmospheric CO_2. In this Comment, we address three issues that relate to this point: (1) the magnitude of the effect, (2) the security of the existing sediment carbon stock, and (3) the mismatch in timescales. Despite these limitations, blue carbon ecosystems are important ecologically and can play a role in short-term carbon sequestration.

We discuss each of these points in turn and then suggest some important messages to communicate to the public, including how blue carbon and other nature-based solutions fit into the range of mitigation options available.

Magnitude of the effect

The global rate of blue carbon burial in seagrass meadow sediment has been greatly overestimated as a result of systematic methodological problems[3,4]. Briefly, most global estimates neglect the effects of sediment mixing (wave mixing or bioturbation), which overestimates sedimentation rates; neglect remineralization of organic carbon in surface sediment, which overestimates carbon burial rates; include terrigenous organic carbon, much of which would have been buried even in the absence of the seagrass meadow; and extrapolate from a few sites with tropical species that have extensive, carbon-rich root mattes to the whole global extent of seagrass habitat[3]. Also, many estimates of organic carbon accretion do not consider the effect of

[1] Fisheries and Oceans Canada, Institute of Ocean Sciences, 9860 W. Saanich Rd. PO Box 6000 Sidney, BC V8L 4B2, Canada.
✉email: Sophia.johannessen@dfo-mpo.gc.ca

$CaCO_3$ formation, which releases carbon to the atmosphere and negates a variable fraction of the drawdown associated with organic carbon burial[5] or the release of CH_4 or N_2O from seagrass meadows and salt marshes[6].

Even the most optimistic estimates suggest that full restoration of mangrove, salt marsh and seagrass ecosystems would only provide an ongoing sink equivalent to 3% of current global anthropogenic emissions[1]. Full restoration is unlikely[1], and the 3% estimate relies on carbon burial rates that are almost certainly too high[3].

Existing sediment carbon stock is a liability, not an asset

Blue carbon stock refers to the inventory of organic carbon stored over a defined depth (often 1 m) in the sediment of vegetated coastal ecosystems. Most blue carbon papers quantify sediment carbon stock, rather than ongoing burial rates[7]. The existing stock is buried in sediment but no longer draws down any more carbon dioxide from the atmosphere. In fact, existing sediment carbon stock represents a potential liability, i.e., an insecure reservoir of carbon that could be released into the atmosphere in the future. This is an important factor that has been largely overlooked in the public discussion of offsetting schemes.

When a seagrass meadow dies or a forest burns, some of the stored carbon is re-released into the atmosphere[8]. Existing stocks are increasingly threatened as a result of climate change, both by sea-level rise[9] and by episodic marine heatwaves[8]. The magnitude of the release of carbon as a result of these processes is unknown, but integrated over a long enough time, it could easily become as large as or larger than ongoing burial. Accretion is gradual and incremental, while release is episodic and highly variable.

Carbon offsets for "avoided emissions" offer to balance additional emissions, such as airplane flights, against no change in carbon stock, which almost inevitably leads to an increase in net emissions. Protecting blue carbon ecosystems also protects their capacity to continue to absorb and bury carbon dioxide. One could argue that offsets for protecting the opportunity for future burial are different from offsets for protecting existing stock, but even the former cannot meaningfully offset fossil carbon emissions for the various reasons discussed in this Comment.

Timescale mismatch

Even if we exclude the possibility of avoided emissions offsets, a fundamental problem with the idea of blue carbon offsets for fossil fuel emissions is the orders of magnitude difference in timescales (Fig. 1). The modern carbon cycle acts on timescales of days to about a century, or up to a few thousand years in the case of equilibration with the deep ocean[10] (Fig. 1). Carbon exchanges

Box 1

a) Blue carbon in the media

- The Guardian (UK), Nov. 4, 2021: "Blue carbon: the hidden CO_2 sink that pioneers say could save the planet"[20]
- Australian Broadcasting Corporation, Sept. 8, 2022: "The carbon-fixing superpower of wetlands, salt marshes and sea meadows"[21]
- Canadian Broadcasting Corporation, August 17, 2022. "The 'secret weapon' in fight against climate change—planting eelgrass"[22]

b) Equivalency between fossil fuel emissions and uptake by vegetation in science, media and non-governmental organizations

- Macreadie et al., 2021: "BCE restoration [of mangroves, salt marshes and seagrass meadows]... could draw down an additional 841 (621–1,064) Tg CO_2e per year by 2030, collectively amounting to ~3% of global emissions (based on 2019 and 2020 global annual fossil fuel emissions)."[1]
- CTV News online, Nov. 2, 2022. "...blue carbon ecosystems can mitigate the release of 1.7 million tonnes of CO_2 by the year 2030, which is the equivalent to 3.4 million barrels of oil."[23]

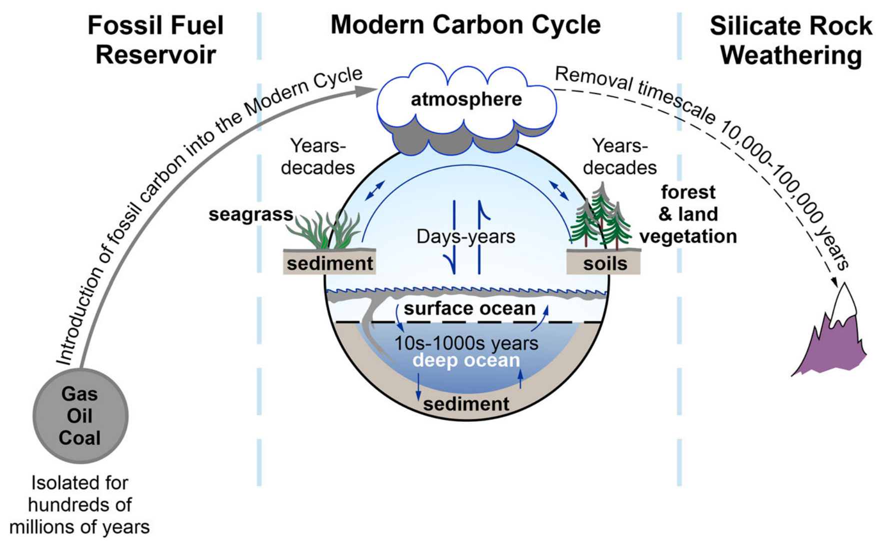

Fig. 1 Carbon cycle timescales. Carbon exchanges among atmosphere, surface ocean, vegetation and soils on a timescale of days to ~100 years. Equilibration with the deep ocean takes years to thousands of years. These processes collectively comprise the Modern Carbon Cycle. The release of fossil carbon has caused the build-up of excess CO_2 in the atmosphere. The excess CO_2 is only removed from the modern cycle by silicate rock weathering (10,000 s–100,000 s of years) or by the re-formation of fossil fuels (hundreds of millions of years).

readily among the atmosphere, surface ocean, vegetation and surface sediment: the expansion of a seagrass meadow moves some carbon from the atmosphere into vegetation and surface sediment; a forest fire releases carbon from the trees back into the atmosphere. These processes only represent exchange among the compartments of the active, modern carbon system, and not a true removal from the system[11].

By contrast, fossil fuels have been isolated from the active carbon cycle for hundreds of millions of years[11]. Burning fossil fuels adds ancient carbon into the modern carbon cycle (Fig. 1), increasing the total amount to be distributed among the atmosphere, vegetation, etc. The timescale for the removal of the excess carbon dioxide by natural processes is tens of thousands to hundreds of thousands of years for silicate rock weathering[12,13] and hundreds of millions of years for the re-formation of fossil fuels[11]. Moving carbon from one short-term reservoir to another does not remove it from the actively cycling modern system.

It might seem obvious that fossil fuel emissions and uptake by vegetation operate on very different timescales. However, there is a real communication gap on this subject. Although the idea of different timescales has begun to appear in the literature (e.g., ref. [14]), it is common to treat these processes as directly equivalent, as evidenced by carbon offset programs that balance planting vegetation against fossil fuel emissions, and by the comparisons made in many scientific papers and media articles (Box 1b).

Important role of blue carbon ecosystems

Despite the limitations discussed above, blue carbon ecosystems do serve important functions. They provide critical habitat for juvenile fish and other marine species; they protect shorelines from erosion; they provide food security for coastal communities; and they protect existing stocks of organic carbon[1,8,15].

Expanding the area or increasing the carbon burial efficiency of blue carbon ecosystems could draw down some additional CO_2 from the atmosphere in the short term, buying time to implement other actions. Protecting existing blue carbon ecosystems could also help to stabilize the organic carbon already stored in the underlying sediment, preventing future losses.

The importance of communication

There is a great deal of confusion over the role of blue carbon in climate change mitigation. Geoscientists whose work extends over a wide range of timescales might find the points raised in this article to be obvious and the explanation unnecessary. However, the expansion of blue carbon offsetting schemes implies that these points are not widely understood, and some misperceptions are perpetuated by the scientific literature on blue carbon. Whenever the mitigation potential of a vegetated ecosystem is linked to a particular number of cars, tons of coal, etc. (presumably out of an understandable desire to present the information in units that are accessible to the reader), it reinforces the false equivalence between emissions of ancient, fossil carbon and the movement of carbon among compartments within the modern system.

Which mitigation actions to take will not be, ultimately, a scientific decision. The decision will be taken by policy-makers and the general public. The role of scientists is to offer clear information about the different types of actions and what might be achieved by each.

In particular, it would be useful for scientists to communicate how blue carbon and other nature-based solutions fit into the range of options for mitigation. Potential climate change mitigation actions can be divided into three categories.

1. Eliminating fossil fuel emissions. Stopping the emissions of ancient carbon would stop the increase in the total amount of carbon in the modern system and stop making the problem worse. This would not, by itself, reverse any of the effects of previous emissions.
2. Expanding blue carbon ecosystems (and/or terrestrial equivalents). This could move some carbon from the atmosphere into vegetation, soils and sediments in the short term. Storage in vegetation and surface sediment is not a secure, long-term sink, but it could buy time to consider further options.
3. Enacting large-scale technological solutions. These include bioenergy with carbon capture and storage[16]; the injection of liquified CO_2 into basaltic rocks, where it becomes a solid mineral[17]; enhanced weathering; and large-scale alkalinization of the ocean[18]. These options could possibly reverse some of the climate change effects already experienced. However, their risks and effectiveness are still largely unknown[19].

Expanding blue carbon ecosystems provides ecological and social benefits, as well as some short-term carbon sequestration, but it cannot truly offset fossil fuel emissions. Clearer communication of the true mitigation potential of different types of management actions would support informed decision-making.

Received: 29 June 2023; Accepted: 23 October 2023;
Published online: 08 November 2023

References

1. Macreadie, P. I. et al. Blue carbon as a natural climate solution. *Nat. Rev. Earth Environ.* **2**, 826–839 (2021).
2. Kennedy, H. et al. Seagrass sediments as a global carbon sink: isotopic constraints. *Glob. Biogeochem. Cycles* **24**, GB4026 (2010).
3. Johannessen, S. C. & Macdonald, R. W. Geoengineering with seagrasses: is credit due where credit is given? *Environ. Res. Lett.* **11**, 113001 (2016).
4. Williamson, P. & Gattuso, J.-P. Carbon removal using coastal blue carbon ecosystems is uncertain and unreliable, with questionable climatic cost-effectiveness. *Front. Clim.* **4**, 853666 (2022).
5. Van Dam, B. R. et al. Calcification-driven CO_2 emissions exceed "Blue Carbon" sequestration in a carbonate seagrass meadow. *Sci. Adv.* **7**, eabj1372 (2021).
6. Rosentreter, J. A., Al-Haj, A. N., Fulweiler, R. W. & Williamson, P. Methane and nitrous oxide emissions complicate coastal blue carbon assessments. *Glob. Biogeochem. Cycles* **35**, e2020GB006858 (2021).
7. Johannessen, S. C. How can blue carbon burial in seagrass meadows increase long-term, net sequestration of carbon? A critical review. *Environ. Res. Lett.* **17**, 093004 (2022).
8. Arias-Ortiz, A. et al. A marine heatwave drives massive losses from the world's largest seagrass carbon stocks. *Nat. Clim. Change* **8**, 338–344 (2018).
9. Lovelock, C. E. & Reef, R. Variable impacts of climate change on blue carbon. *One Earth* **3**, 195–211 (2020).
10. Siegel, D. A., DeVries, T., Doney, S. C. & Bell, T. Assessing the sequestration time scales of some ocean-based carbon dioxide reduction strategies. *Environ. Res. Lett.* **16**, 104003 (2021).
11. Berner, R. A. The long-term carbon cycle, fossil fuels and atmospheric composition. *Nature* **426**, 323–326 (2003).
12. Archer, D. et al. Atmospheric lifetime of fossil fuel carbon dioxide. *Annu. Rev. Earth Planet. Sci.* **37**, 117–134 (2009).
13. Colbourn, G., Ridgwell, A. & Lenton, T. M. The time scale of the silicate weathering negative feedback on atmospheric CO_2. *Glob. Biogeochem. Cycles* **29**, 583–596 (2015).
14. Fankhauser, S. et al. The meaning of net zero and how to get it right. *Nat. Clim. Change* **12**, 15–21 (2022).
15. Hejnowicz, A. P., Kennedy, H., Rudd, M. A. & Huxham, M. R. Harnessing the climate mitigation, conservation and poverty alleviation potential of seagrasses: prospects for developing blue carbon initiatives and payment for ecosystem service programmes. *Front. Mar. Sci.* **2**, 32 (2015).
16. Azar, C., Johansson, D. J. A. & Mattsson, N. Meeting global temperature targets—the role of bioenergy with carbon capture and storage. *Environ. Res. Lett.* **8**, 034004 (2013).
17. Snæbjörnsdóttir, S. Ó. et al. Carbon dioxide storage through mineral carbonation. *Nat. Rev. Earth Environ.* **1**, 90–102 (2020).

18. Hartmann, J. et al. Stability of alkalinity in ocean alkalinity enhancement (OAE) approaches—consequences for durability of CO_2 storage. *Biogeosciences* **20**, 781–802 (2023).
19. Gattuso, J.-P., Williamson, P., Duarte, C. M. & Magnan, A. K. The potential for ocean-based climate action: negative emissions technologies and beyond. *Front. Clim.* **2**, 575716 (2021).
20. The Guardian. *Blue Carbon: The Hidden CO_2 Sink That Pioneers Say Could Save the Planet*. https://www.theguardian.com/environment/2021/nov/04/can-blue-carbon-make-offsetting-work-these-pioneers-think-so (2021).
21. Australian Broadcasting Corporation. *The Carbon-fixing Superpower of Wetlands, Salt Marshes and Sea Meadows*. https://www.abc.net.au/radionational/programs/bigideas/blue-carbon-wetlands-biodiversity-and-climate-change/14041136 (2022).
22. Canadian Broadcasting Corporation. *The 'Secret Weapon' In Fight Against Climate Change—Planting Eelgrass*. https://www.cbc.ca/news/canada/nova-scotia/the-secret-weapon-in-fight-against-climate-change-planting-eelgrass-1.6553071 (2022).
23. CTV News online. *How Protecting Natural Areas in Canada Can Reduce Its Greenhouse Gas Emissions, New Report Reveals*. https://www.ctvnews.ca/mobile/climate-and-environment/how-protecting-natural-areas-in-canada-can-reduce-its-greenhouse-gas-emissions-new-report-reveals-1.6178592 (2022).
24. Project Zero. *Restore & Protect Blue Carbon Ecosystems*. https://www.weareprojectzero.org/blue-carbon (2022).

Acknowledgements

Our mentor and friend Dr. R.W. (Robie) Macdonald initially conceptualized the time-scale idea presented here. The authors thank the Editor and two anonymous reviewers for their comments, which greatly improved the paper. Dr. Doug Wallace and Dr. Iain Dickson offered insightful comments on an earlier draft.

Author contributions

S.C.J. and J.R.C. conceptualized the paper with the late Dr. R. W. Macdonald (see Acknowledgements). S.C.J. and J.R.C. wrote the paper.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s43247-023-01068-x.

Correspondence and requests for materials should be addressed to Sophia C. Johannessen.

Peer review information *Communications Earth & Environment* thanks the anonymous reviewers for their contribution to the peer review of this work. Primary handling editors: Clare Davis. A peer review file is available.